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A THEORETICAL STUDY OF THE MARTIAN IONOSPHERE

by

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ABSTRACT

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A theoretical study, based on a neutral atmosphere composed of 2% carbon dioxide and 98% molecular nitrogen, indicates that the Martian ionosphere would occur higher above the planet's surface than does the terrestrial ionosphere, but at about the same total pressure. The maximum electron density for overhead sun is about 2×10^5 cm^3 as compared to about 10^6 cm^3 on earth. On Mars there may be layers that absorb radio waves more strongly than the normal terrestrial D region.

AUTHOR

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Introduction

The possibility of rocket exploration of Mars necessitates the consideration of the ionosphere likely to be encountered on this planet. The design of communication systems and ionospheric sounding experiments requires a knowledge of ionospheric parameters. Furthermore, if sufficient data on the Martian ionosphere can be obtained then a comparison of this data with the theoretical model allows an evaluation of our theory.

The construction of a model ionosphere requires knowledge of the neutral atmosphere, sources of ionization and the processes that control the motion and loss of the ionized gas. The following sections will discuss each of these items in turn. Then we will present a model ionosphere and compare it with a typical model of the earth's ionosphere. The numerical results are for overhead sun and a sunspot number of about 50. However, we will discuss the effect of changing solar position and changing sunspot number. Finally, we will discuss the effect of changing the composition of the neutral atmosphere.

Data

Almost all our knowledge of the structure of the Martian ionosphere is the result of theoretical studies by Goody (1957) and Chamberlain

(1961). We will use the atmospheric model developed by Chamberlain (see figure 1). It should be noted in figure 1 that the Martian upper atmosphere contains an appreciable amount of atomic oxygen, but that the ratio O/N_2 is smaller on Mars as compared to earth at a fixed O density. The atomic oxygen on Mars and earth formed by photodissociation of CO_2 and O_2, respsectively. There is also a Martian layer of molecular oxygen with a peak density estimated to be about 5×10^{12} cm^3 occurring at about 110 km. This molecular oxygen is formed by the recombination of the oxygen atoms obtained by the photodissociation of the carbon dioxide.

The surface gravity of Mars and earth are in the ratio of 2.5. As a result, even though the surface densities are smaller on Mars, above about 30 km the Martian densities exceed the terrestrial densities for a corresponding height.

Ionization by solar X ray and ultra violet radiation seems adequate to explain most of the ionization in the terrestrial ionosphere. In this paper we will consider the solar EM flux data of Hinteregger (1961) and Kreplin (1961) extrapolated to the distance of Mars. If particle ionization is important then our photoionization rates will be lower limits.

The solar fluxes have been grouped into several categories according to ionization cross sections and efficiencies. With these data and the model atmosphere given in figure 1 the Martian photoionization rates of O and N_2 have been computed and are presented in figure 2. The peak rate for O_2 is estimated to be about 600 cm^{-3} sec^{-1}.

Theory

Recombination loss of electrons is an important process that must be considered in any ionospheric theory. The two main loss processes are:

$$xy^+ + e \rightarrow x + y \qquad \text{dissociative recombination} \qquad (1)$$

$$xy^+ + e \rightarrow xy + h\nu \qquad \text{radiative recombination.} \qquad (2)$$

It is important to realize that dissociative recombination is much faster than radiative combination, the rate coefficients being 10^{-6} - 10^{-9} cm^3 sec^{-1} and about 10^{-12} cm^3 sec^{-1} respectively. The atomic ions recombine radiatively unless they can undergo reactions such as the following:

$$x^+ + yz \rightarrow xy^+ + z \qquad \text{atom-ion exchange} \qquad (3)$$

$$x^+ + yz \rightarrow yz^+ + x \qquad \text{charge exchange,} \qquad (4)$$

followed by dissociative recombination of the resulting molecular ion. The exchange coefficients are usually of the order of 10^{-10} - 10^{-12} cm^3 sec^{-1}. The sequence of an exchange reaction and dissociative recombination is often much faster than radiative recombination.

According to current theories of the terrestrial ionosphere the ions undergo the following reactions:

$$O^+ + O_2 \rightarrow O_2^+ + O \qquad (5)$$

$$O^+ + N_2 \rightarrow NO^+ + N \qquad (6)$$

$$O_2^+ + e \rightarrow O + O \qquad (7)$$

$$N_2^+ + e \rightarrow N + N \qquad (8)$$

$$NO^+ + e \rightarrow N + O \qquad (9)$$

However, the above reactions are not adequate in that reaction (8) will not reduce the density of N_2^+ to observed values [Lytle and Hunten, 1962; Norton et al, 1963]. We will therefore include the reaction:

$$N_2^+ + O \rightarrow NO^+ + N. \tag{10}$$

It must be pointed out that this reaction is not accepted by all aeronomists.

Model Ionosphere

The Martian ionosphere will also contain CO^+ and CO_2^+. However, we will assume that these ions are lost by dissociative recombination and assume by analogy with O_2^+ and NO^+ [Kasner, 1961; Doering and Mahan, 1962] that the rate coefficients are of the order of 10^{-7} cm^3 sec^{-1}. Thus, since the density of CO and CO_2 is small compared to N_2 these two ions will contribute very little to the total ion content and will not be considered any further.

The ion N^+ has been detected in the earth's ionosphere and contributes about 5% of the ions near the peak of the F2 layer [Mirtov, 1962]. It could be argued that in the Martian atmosphere the formation of N^+ would be at least comparable. On the other hand the loss of N^+ is likely to involve an exchange reaction with O and O_2 and therefore the rate of loss of this ion is likely to be smaller on Mars with the model atmosphere chosen. The net result would be a higher density of N^+ on Mars. However, considering the paucity of information concerning atomic nitrogen even in the earth's atmosphere, we will, with some reluctance, ignore this ion in the remainder of the paper.

In this paper we will not consider the ionization of the light atoms hydrogen and helium which are important in the terrestrial ionosphere only well above the peak electron density. In fact, because of the lower Martian gravity these atoms may be less plentiful on Mars.

Neither will we consider the ionization of minor constituents such as NO which, according to Nicolet and Aikin (1960), contributes a major part of the normal terrestrial D region, a region of low electron density below the E region (see figure 3). However, it should be pointed out that the X rays and cosmic rays which contribute to the lower terrestrial D region may result in higher electron densities on Mars. Such layers strongly absorb radio waves and can severely hinder radio communication, especially during solar flares when the solar X-ray flux is greatly increased.

The argument for such an enhancement of electron density is based on the current D region theory in which an important loss of electrons is attachment to O_2 to form O_2^-. On Mars, at the pressures at which the relevant X rays are absorbed, the density of O_2 is neglible according to the model atmosphere in figure 1. However, there is the possibility of forming some minor constituent which would serve the same role as O_2.

The electron layer formed by the ionization of O_2 by solar radiation between 912-1030A results in the combination of fairly high electron density with high neutral density which implies a high electron-neutral collision frequency (see the ledge below the Martian E layer in figure 3). Such a layer absorbs radio waves and may be more strongly absorbing than the terrestrial D region. It should be noted that this layer would be a permanent daytime fixture while the solar flare layer mentioned above is a transient phenomenon.

The continuity equation for the various ions in the E and F1 regions have been solved for the photochemical equilibrium ion density and electron density. The electron density is compared with a terrestrial profile in figure 3. In general corresponding ledges occur at a higher height on Mars and have a lower density.

Photochemical equilibrium is not always appropriate; for example, at some height diffusion of the ionized gas will become important. The height at which this occurs can be found by comparing the times of diffusion and recombination. Above the height where these times are about equal diffusion will be the controlling process and below this height recombination and photoionization will be the controlling processes.

The terrestrial F2 peak does not correspond to a peak of photoionization, but occurs because the loss rate decreases with height faster than the production rate. Diffusion tends to reduce the height at which the peak occurs. Since the Martian and terrestrial ionospheres are similar we may well suspect that there will be a Martian F2 layer. The height and magnitude of such a layer can be estimated by using the scaling laws presented by Rishbeth and Barron (1960). These scaling laws state that the diffusion and recombination times are comparable at the peak and that the peak electron density is about equal to the photochemical equilibrium density. The Martian peak labeled F2 in figure 3 was estimated using these scaling laws. At this peak the N_2^+ and O^+ densities are comparable; however, O^+ should become the dominant ion above the peak. It was assumed that above the peak the electron density was distributed according to diffusive equilibrium with the atomic oxygen ion.

The diurnal and seasonal variation of the Martian layers will in general be similar to the corresponding terrestrial layers. The daytime variation of the E and F1 layers will be proportional to $\cos^m \chi$. Where χ is the solar zenith angle and m is a number in the vicinity of 0.25 - 0.35. The electron densities at night will be at least one to two orders of magnitude less than during the day. The diurnal variation of the O_2^+ layer will also depend on $\cos^m \chi$, but the seasonal variation may depend on changes in the neutral atmosphere.

The variations of the terrestrial F2 layer are not simple and not well understood. However, if we suppose that the behavior of the F2 layer is similar on these two planets then the Martian F2 densities will decrease by a factor of about 10 from day to night and the peak F2 density will be greater in winter than in summer.

There will be an annual variation in the Martian ionosphere due to the varying Mars-sun distance. Since the aphelion and perihelion distances are 2.49×10^8 km and 2.07×10^8 km respectively, the ratio of the ionizing solar flux at these two points will be 1.45. The corresponding ratio for earth is 1.06.

To a good approximation the average values of maximum densities of the terrestrial layers follow solar activity. Thus for Zurich sunspot numbers 0, 50 and 150 the E and F1 layer maximum densities are in the ratio 1:1.2:1.7 and 1:1.2:1.6 respectively. One would expect essentially the same ratios for the corresponding Martian layers. The ratios for the terrestrial F2 layer are 1:1.7:4, but because of the complex nature of this layer these values cannot be simply adapted to the Martian F2. A similar effect should occur on Mars.

The terrestrial magnetic field affects the latitudinal variation of the F2 electron densities. In particular there is a belt at 10 - 20° geomagnetic latitude, parallel to the geomagnetic equator where peak densities are enhanced by about a factor of 2. If Mars has a magnetic field similar effects are likely to occur.

Discussion

In the previous sections we were able to construct a model Martian ionosphere by assuming a model atmosphere, using observed solar fluxes, and considering the recombination processes thought to be operative in the terrestrial ionosphere. The Martian and terrestrial ionospheres are similar, the main differences being the smaller peak density and greater heights on Mars (see figure 3). The Martian peak density corresponds to the F1 layer rather than the F2 layer as on earth. The layer corresponding to ionization of O_2 occurs at a higher total pressure level on Mars and thus may strongly absorb radio waves. On the other hand the layers corresponding to ionization by X rays and cosmic rays occur where O_2 density is small and thus the electron density may be greater than it would be on earth. Again these layers would strongly absorb radio waves. The ions CO^+ and CO_2^+ would exist in the Martian ionosphere, but would contribute only a small fraction of the total ion density. The ion N^+ could contribute significantly to the ion density, but was not considered in this paper because of lack of data.

Finally, we should comment that the model ionosphere developed depends on the model atmosphere assumed. If the Martian atmospheric ratio of CO_2/N_2 were significantly larger than assumed in this paper then: (a) the ratio of O/N_2 would be larger in the upper atmosphere and the F2 density would be more dense, (b) CO^+ might contribute significantly to the lower ionospheric ion density, and (c) O_2 would be formed at a lower total pressure and thus the O_2^+ layer would not strongly absorb radio waves.

Acknowledgments

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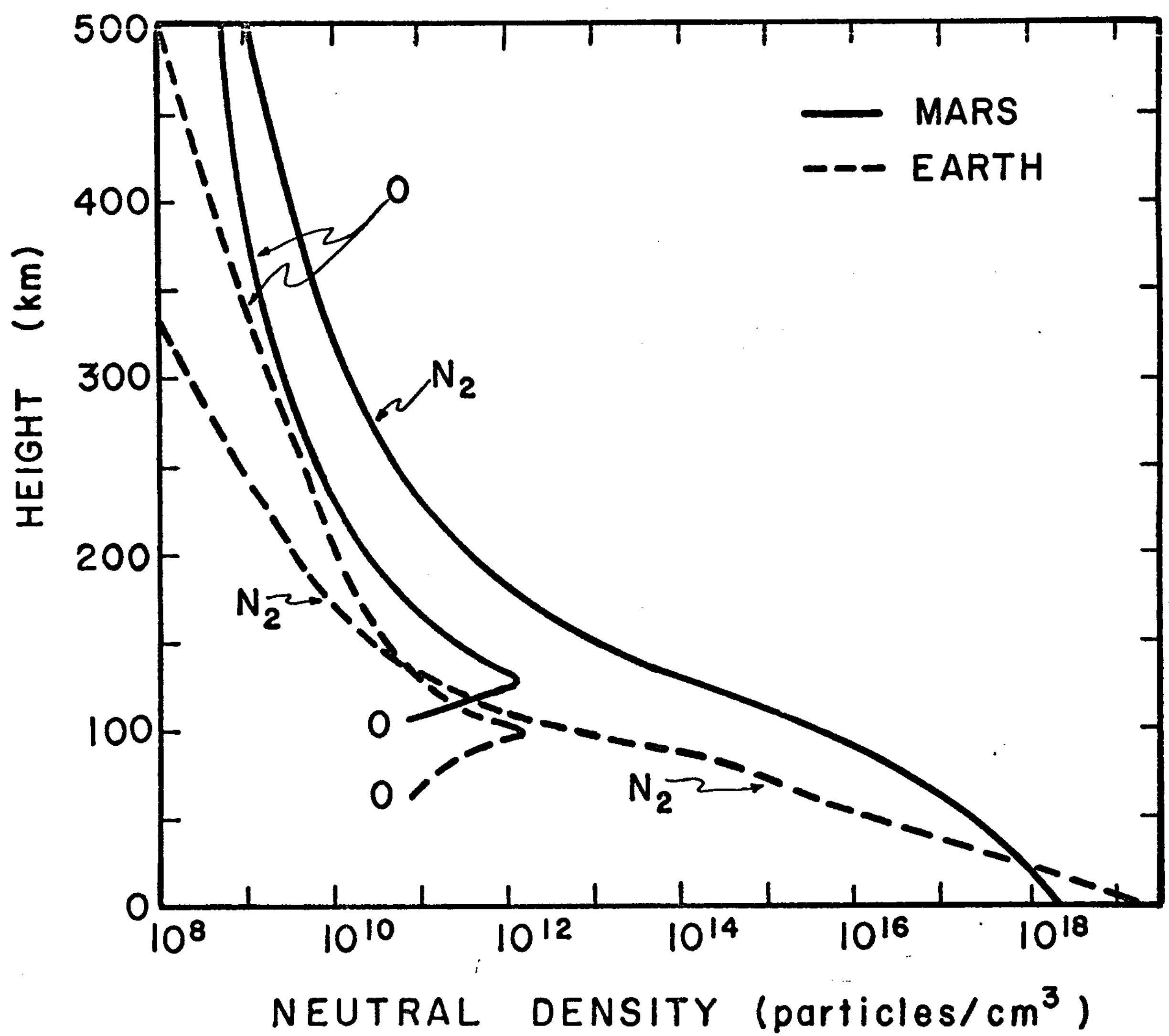
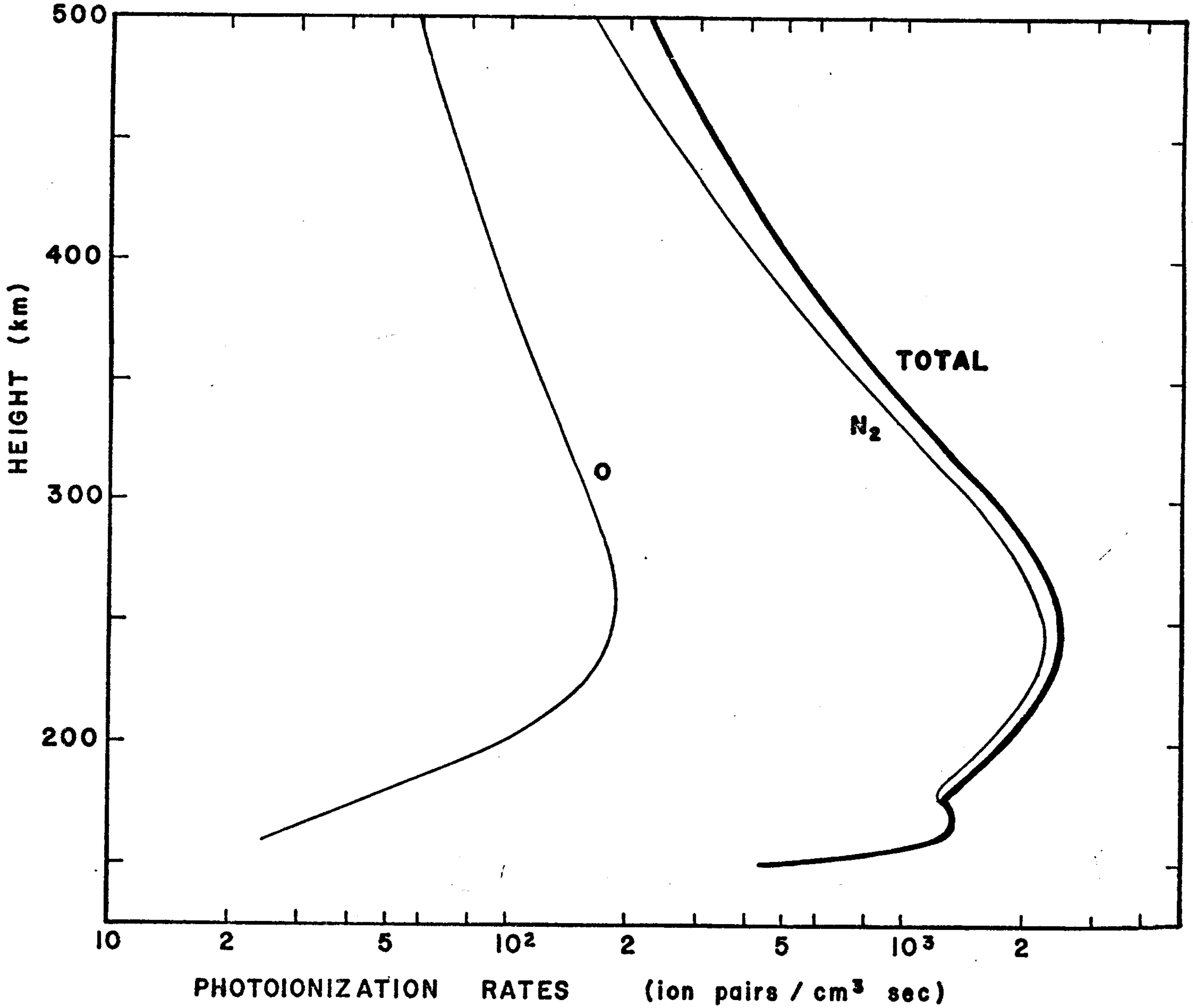
Captions

Figure 1. Neutral density versus height for earth and Mars

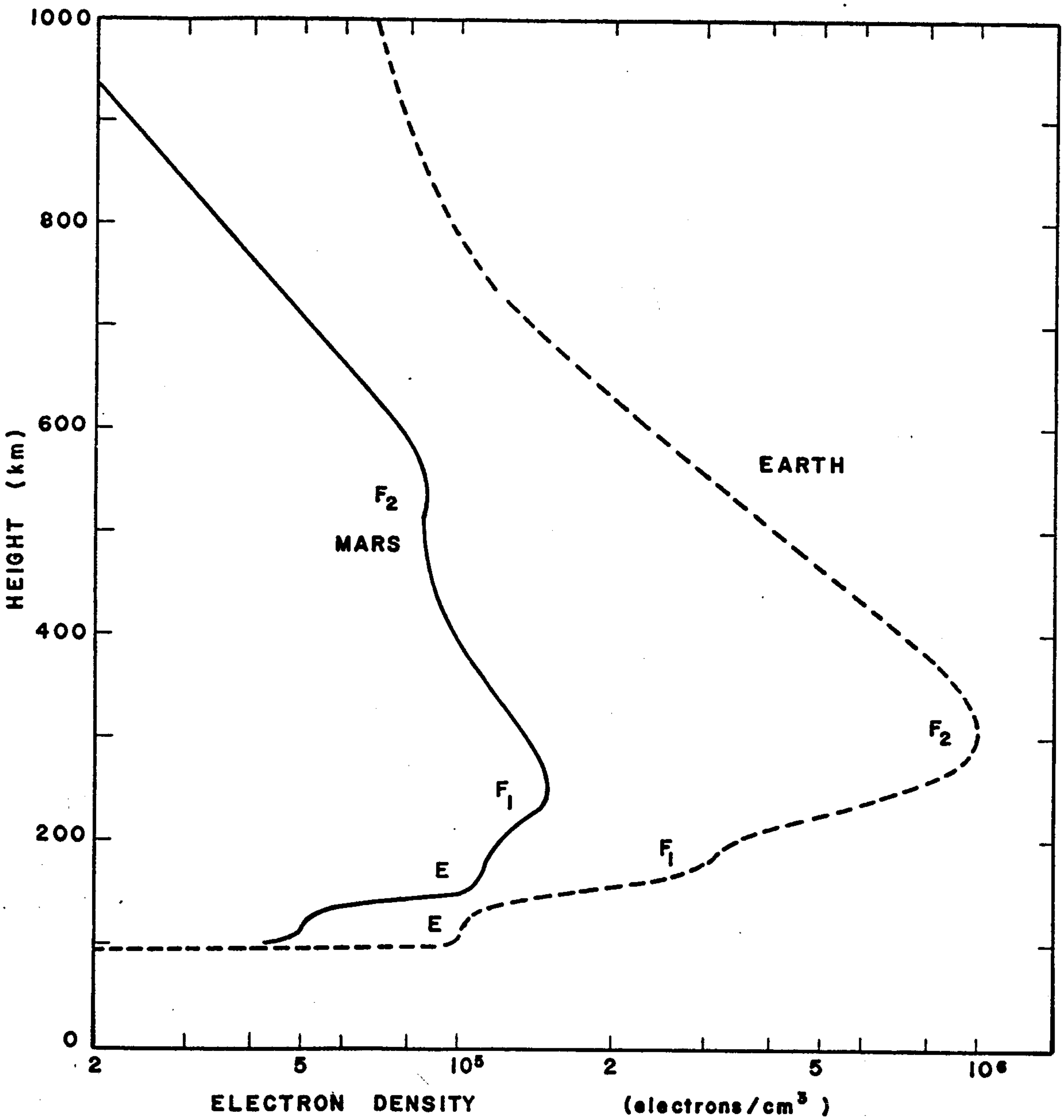
Figure 2. Rate of photoionization for O and N_2 versus height for Mars

Figure 3. Electron density versus height for earth and Mars


MARS
EARTH
O
N2
N2
O
O
N2
HEIGHT (km)
500
400
300
200
100
0
10^8
10^10
10^12
10^14
10^16
10^18
NEUTRAL DENSITY (particles/cm^3)



500
400
300
200
HEIGHT (km)
O
N2
TOTAL
10
2
5
10²
2
5
10³
2
PHOTOIONIZATION RATES (ion pairs / cm³ sec)



1000
800
600
400
200
0
HEIGHT (km)
2
5
10^5
2
5
10^6
ELECTRON DENSITY (electrons/cm^3)
MARS
EARTH
F2
F1
E
F2
F1
E

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